N-MEMs

Sensing & Actuation

Lecture 13

(Source: Chap 3 & 5; Liu & Chang)

Topics to be covered

- Ways the conductivity of semiconductor material may be controlled
- Calculations of conductivity (or resistivity) of semiconductor material
- Cantilever beam force calculations
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Key Concept-1: Conductivity of Semiconductor Material

- A semiconductor is fundamentally different from conductors (e.g., metals) and insulators (e.g., glass or rubber). As its name suggest, a semiconductor is a material whose conductivity lies between that of a perfect insulator and a perfect conductor.
- More importantly, the conductivity of a semiconductor material can be controlled by a variety of means, such as
  - intentionally introduced impurities,
  - externally applied electric field,
  - charge injection,
  - ambient light, and
  - temperature variations.

  These control "levers" lead to many uses of the semiconductor materials, including bipolar junction transistors, field effect transistors, solar cells, diodes, and sensors for temperature, force, and concentrations of chemical species (e.g., chemical field effect transistors, or ChemFET).

Calculation of Conductivity of Semiconductor

- Diffusion
- Ion Implantation

Concentration

$$n = p \equiv n_i$$

$$n_i^2 = 4\left(\frac{4\pi^2 m_n^* m_p^* k^2 T^2}{h^2}\right)^{3/2} e^{\frac{-E_g}{kT}},$$

$$n_0 p_0 = n_i^2.$$

Consider a piece of silicon under room temperature and thermal equilibrium. The silicon is doped with boron with a doping concentration of 10^{16} atoms/cm^3. Find the electron and hole concentrations.

the value of n_i for Si at room temperature is only $1.5 \times 10^{10}/\text{cm}^3$,

$$n_0 \approx \frac{n_i^2}{p_0} = 2.25 \times 10^4/\text{cm}^3.$$

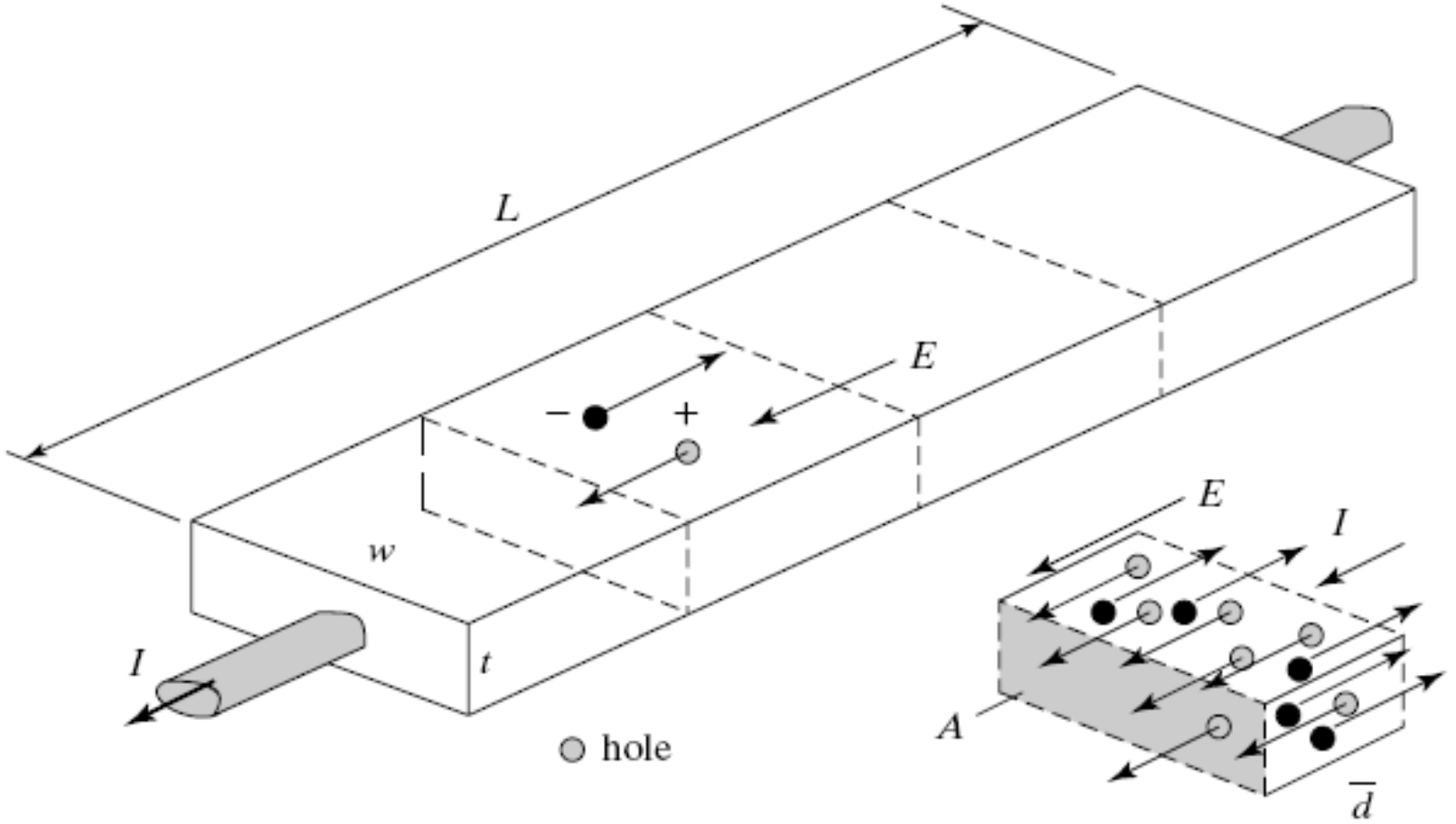


FIGURE 3.1

A semiconductor resistor.

The conductivity contributed by electrons is derived

$$\sigma_n = \frac{J}{E} = \frac{\frac{I_A}{A}}{E} = \frac{\frac{Q}{A\bar{l}}}{E} = \frac{\frac{(nA\bar{d}q)}{A\bar{l}}}{E} = \frac{n\bar{V}q}{E} = n\mu_n q$$

$$\rho = \frac{1}{\sigma} = \frac{1}{\sigma_n + \sigma_p} = \frac{1}{q(\mu_n n + \mu_p p)}.$$

$$\sigma = \frac{J}{E}.$$

$$J = \sigma E.$$

$$E = \rho J.$$

The intrinsic carrier concentration (n_i) of silicon under room temperature is $1.5 \times 10^{10}/\text{cm}^3$. A silicon piece is doped with phosphorus to a concentration of $10^{18}\,\text{cm}^{-3}$. The mobility of electrons and holes in the silicon are approximately $1350\,\text{cm}^2/\text{V-s}$ and $480\,\text{cm}^2/\text{V-s}$, respectively. Find the resistivity of the doped bulk silicon.

$$n_0 = 10^{18}\,\text{cm}^{-3}$$

$$p_0 = \frac{n_i^2}{n_0} = 225\,\text{cm}^{-3}$$

The resistivity of the doped silicon is calculated by plugging in the following formula

$$\rho = \frac{1}{\sigma} = \frac{1}{q(\mu_n n_0 + \mu_p p_0)}$$

$$= \frac{1}{1.6 \times 10^{-19} \times (1350 \times 10^{18} + 480 \times 225)}$$

$$= 0.0046 \frac{V \cdot s \cdot \text{cm}}{C} = 0.0046 \frac{V \cdot \text{cm}}{A} = 0.0046 \Omega \cdot \text{cm}$$

How may we understand the Static & Dynamic Behaviors of MEMS under loading Conditions?

Newton's laws	Statement
Newton's First Law of Motion (The Law of Inertia)	Every object in a state of uniform motion tends to remain in the state of motion unless an external force is applied to it.
Newton's Second Law of Motion	The relationship between an object's mass m, its acceleration a, and the applied force F is $F = ma$. Acceleration and forces are vectors. The direction of the force vector is the same as the direction of the acceleration vector.
Newton's Third Law of Motion	For every action there is an equal and opposite reaction.

Mechanical Properties: Stress & Strain

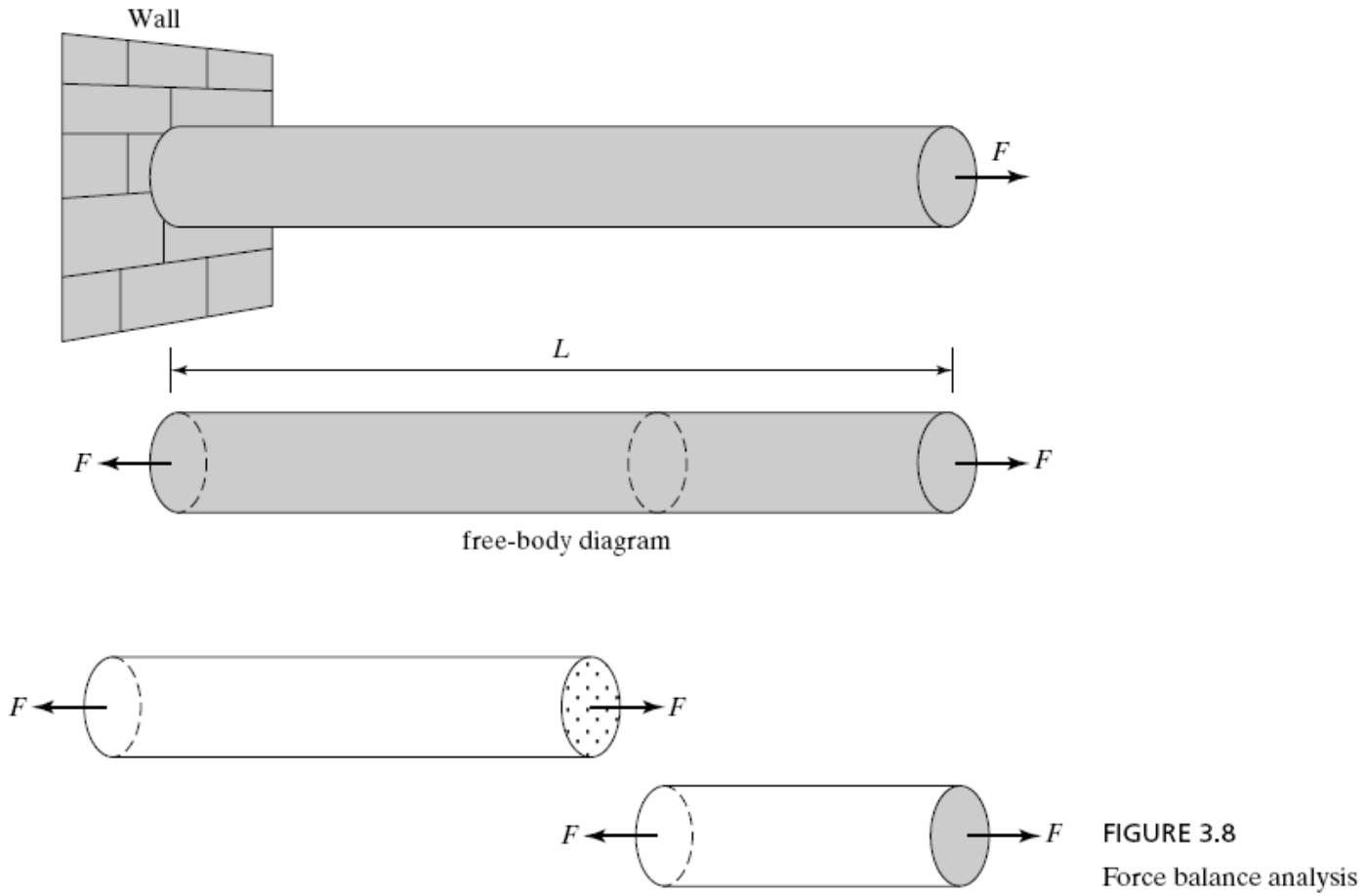
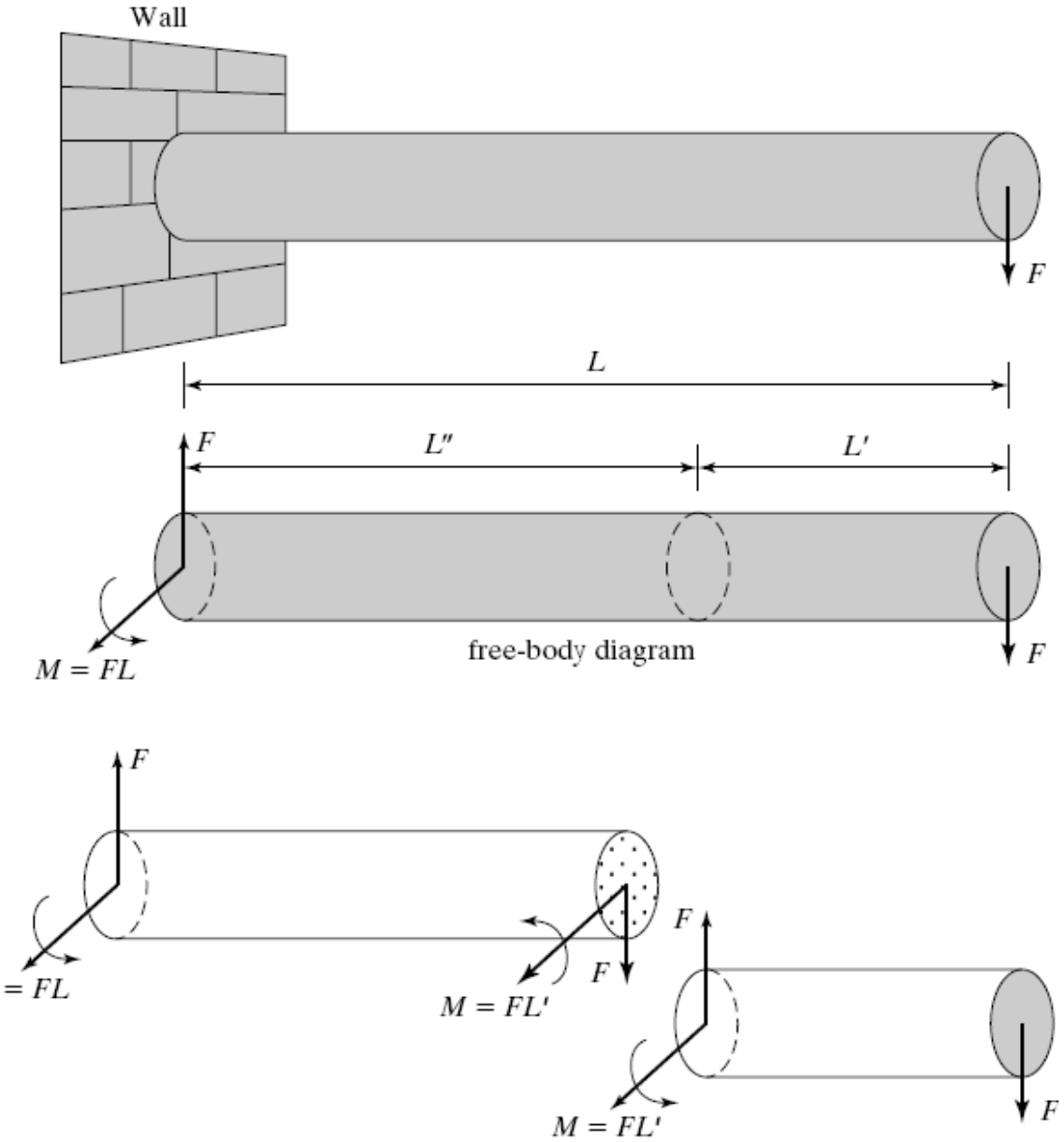


FIGURE 3.8
Force balance analysis

Force & Moment Balance Analysis

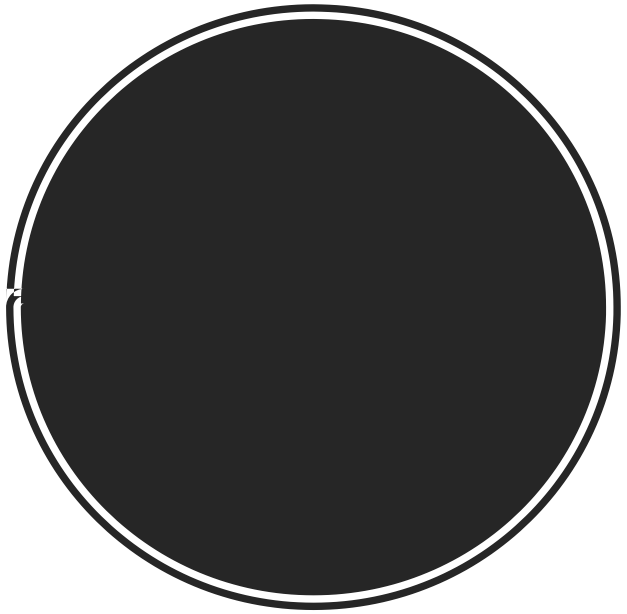


At any chosen cross section, a continuously distributed force is found acting over the entire area of the section. The intensity of this force is called the stress. If the stress acts in a direction perpendicular to the cross section, it is called a **normal stress**. The normal stress, commonly denoted as σ, is defined as the force (F) applied on a given area (A),

$$\sigma = \frac{F}{A}. \tag{3.19}$$

The SI unit of stress is N/m^2, or Pa.

A cylindrical silicon rod is pulled on both ends with a force of 10 mN. The rod is 1 mm long and 100-μm in diameter. Find the stress and strain in the longitudinal direction of the rod.



$$\sigma = \frac{F}{A} = \frac{10 \times 10^{-3}}{\pi\left(\frac{100 \times 10^{-6}}{2}\right)^2} = 3.18 \times 10^5 \text{ N/m}^2$$

$$s = \frac{\sigma}{E} = \frac{3.18 \times 10^5}{130 \times 10^9} = 2.4 \times 10^{-6}$$

Cantilever Beam Spring

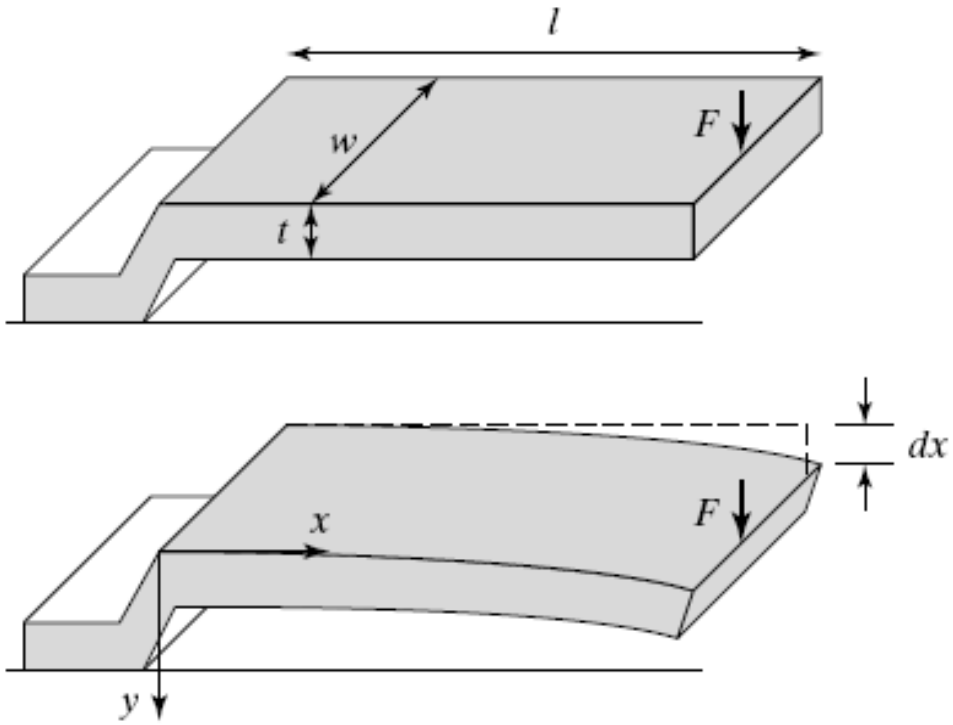


FIGURE 3.19

Schematic diagram of a fixed-free cantilever beam spring.

$$I = \frac{wt^3}{12} \qquad I = \frac{\pi R^4}{4}.$$

Two cantilever beams of the same length and material, one with a cross section of 100 μm by 5 μm, and a second one with 50 μm by 8 μm. Which one is more resistant to flexural bending (i.e., stiffer?)

Calculations for Stiffness

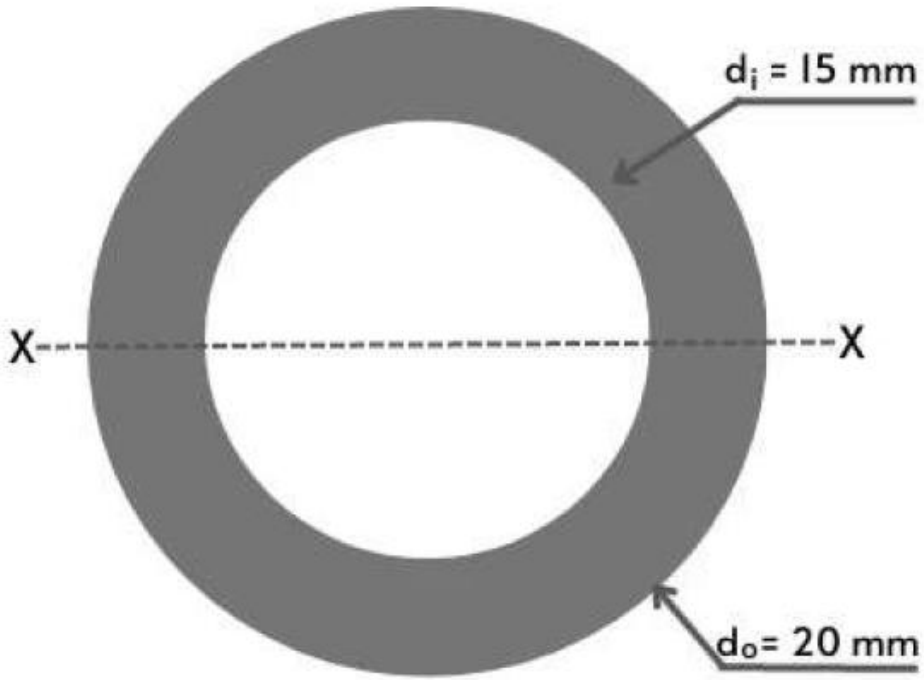
Solution. The moment of inertia of the first beam is

$$I_1 = \frac{wt^3}{12} = \frac{100 \times 10^{-6} \times (5 \times 10^{-6})^3}{12} = 1.04 \times 10^{-21}\ \mathrm{m}^4.$$

For the second beam, we have

$$I_1 = \frac{wt^3}{12} = \frac{50 \times 10^{-6} \times (8 \times 10^{-6})^3}{12} = 2.13 \times 10^{-21}\ \mathrm{m}^4$$

1] Find the bending stiffness of the lever with a modulus of elasticity of 210 GPa and with a hollow circular cross-section.



Given:

E = 210 Gpa = 210 × 10^3 N/m^2

d_i = 15 mm

d_o = 20 mm

B.S. = Modulus of elasticity x Moment of inertia

Post-Mid Assignment

Problem 3: Design

A phosphorous-doped silicon resistor is 100 μm long, 2 μm wide, and 0.5 μm thick. The doping concentration is 10^{17} atoms/cm^3. The electron mobility (μ_n), which is a function of the doping concentration, is approximately 1350 cm^2/(Vs). The hole mobility is approximately 480 cm^2/(Vs). What are the concentrations of electrons and holes under thermal equilibrium at room temperature? Find the resistivity of the material and the total resistance.

Problem 4: Design

Repeat Problem 3 assuming the resistor is doped with boron. In this case, holes will be the majority carrier.

Problem 5: Design

Repeat Problem 3 assuming the doping concentration of phosphorous is 10^{11} atoms/cm^3.

Post-Mid Assignment

Problem 6: Design

A silicon wafer is doped by boron ion implantation followed by thermal activation. Ion implantation is conducted at a dose of 10^{14} atoms/cm^2. The depth of the doped region (junction depth) is determined by the original depth of high-energy ion penetration and thermal diffusion during the activation step. Assume the junction depth is 1 μm and the concentration is uniform through the depth of the doped layer. What is the doping concentration?

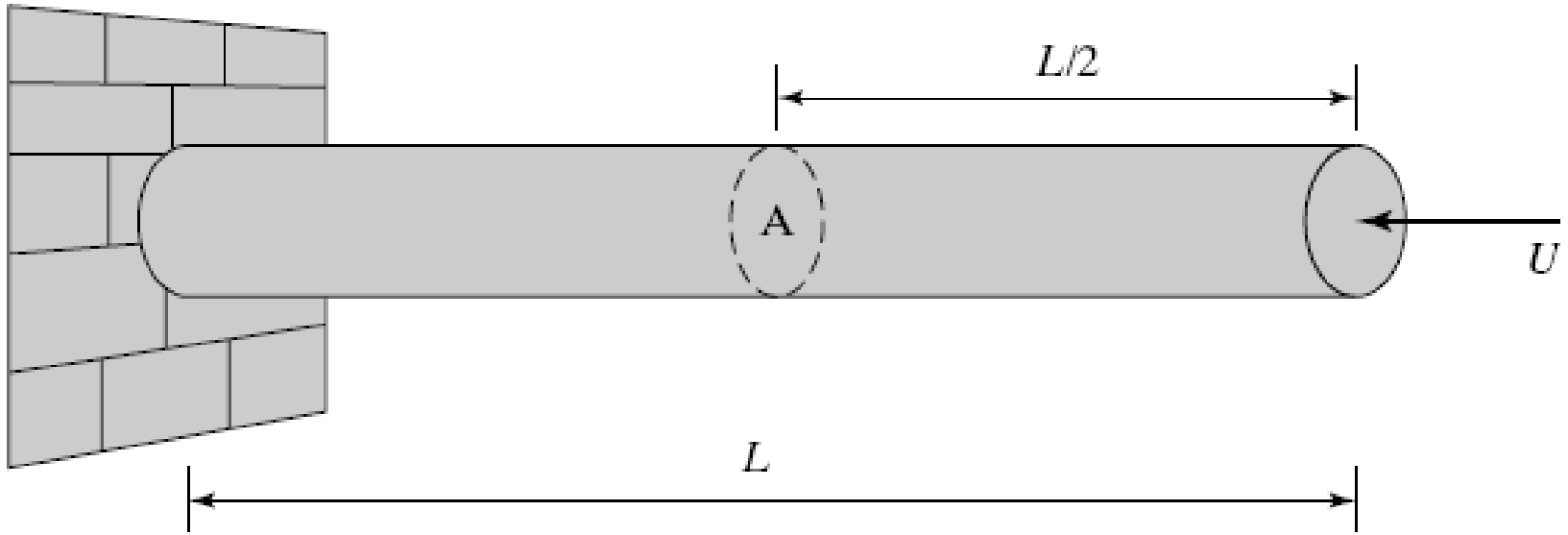
Problem 7: Design

A boron doped silicon resistor has a sheet resistivity of 50$\Omega/\square$. The length and width of the resistor is 10 μm and 0.5 μm, respectively. Find the total resistance of the resistor. If the thickness of the resistor is known to be 0.3 μm, what is the resistivity and the boron doping concentration? What are the concentrations of the majority carrier under thermal equilibrium at room temperature?

Post-Mid Assignment

Problem 13: Design

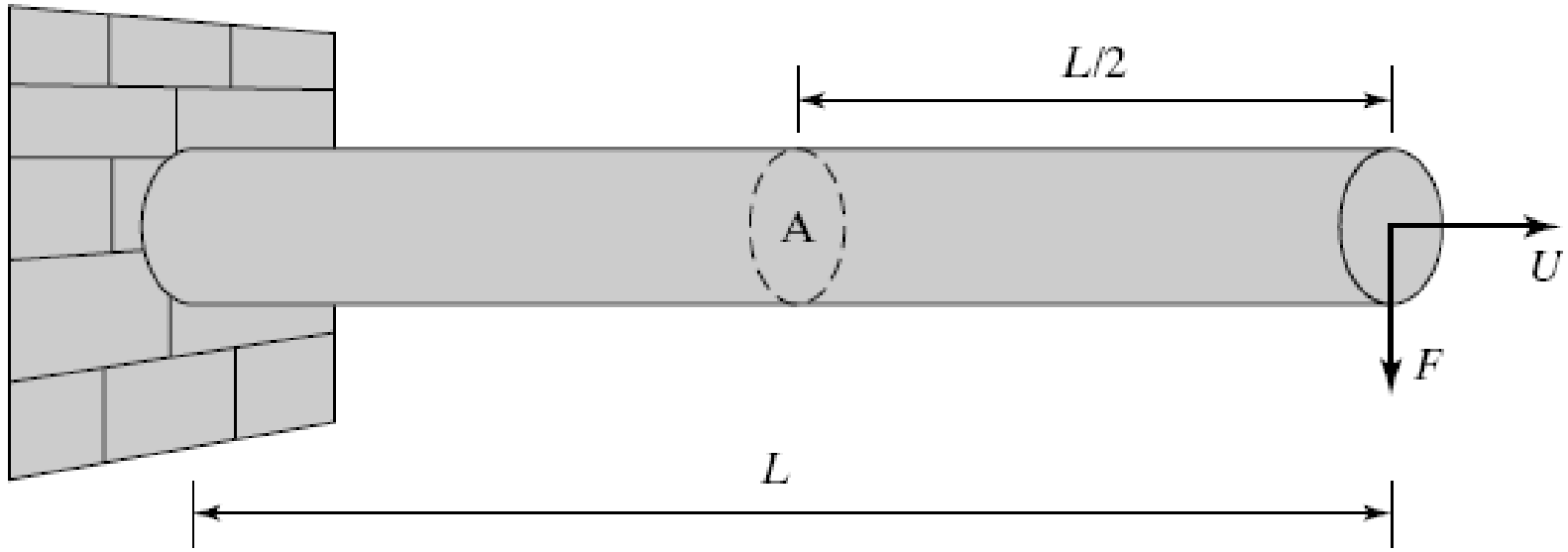
An axial force with magnitude of U is applied at the end of a bar attached to a wall. Find the reactive force and torque (if any) at the anchored end of the bar and at section A.



Post-Mid Assignment

Problem 14: Design

Two independent axial forces with magnitude of U and F are applied at the end of a bar attached to a wall. Find the reactive force and torque (if any) at the anchored end of the bar and at section A. Assume the overall reaction under a combined force is the linear sum of reactions under two forces acting individually.



Post-Mid Assignment

Problem 21: Design

A single crystal silicon bar is 100 μm long, 5 μm wide, and 1 μm thick at room temperature. The bar is doped to a uniform P concentration of 10^{16} atoms/cm^3. Find (a) the moment of inertia and (2) the electrical resistance of the silicon bar.

Problem 26: Design

To build a 20-μm wide fixed-free cantilever beam with a force constant of 10 N/m and a resonant frequency of 10 kHz out of single crystal silicon, find the desired length and thickness of the cantilever beam. The Young's modulus of silicon is 120 GPa. The density of the silicon material is 2330 Kg/m^3. Selected the correct answer from choice below and explain the reasoning behind your choice.

(3) Length = 6.4 mm and thickness = 351 μm.
(4) Length = 2.9 mm and thickness = 75.7 μm.
(3) Length = 143 mm and thickness = 3.65 mm.
(4) None of the above.

Principles of Thermal Actuation

- Actuation of micro scale devices and structures can be achieved by injecting or removing heat.
- Changes in temperature profile in turn result in mechanical displacement or force output, through thermal expansion, contraction, or phase change.
- The temperature of a microstructure can be raised by absorption of electromagnetic waves (including light), ohmic heating (joule heating), conduction, and convection heating.
- Cooling can be achieved via conduction dissipation, convection dissipation, radiation dissipation, and active thermoelectric cooling.

Inkjet Printers

- Thermal actuation is used in commercial MEMS products. Many ink jet printers today eject ink droplets using thermal expansion of liquid inks. A schematic diagram of a single thermal ink jet printer nozzle is shown in Figure 5.1.

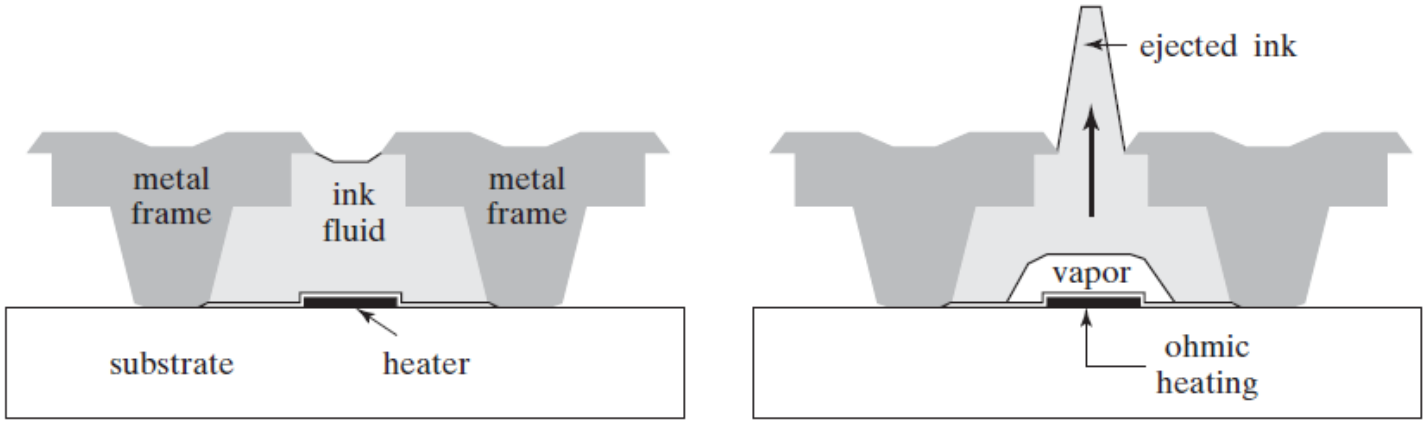


FIGURE 5.1

The principle of ink ejection.

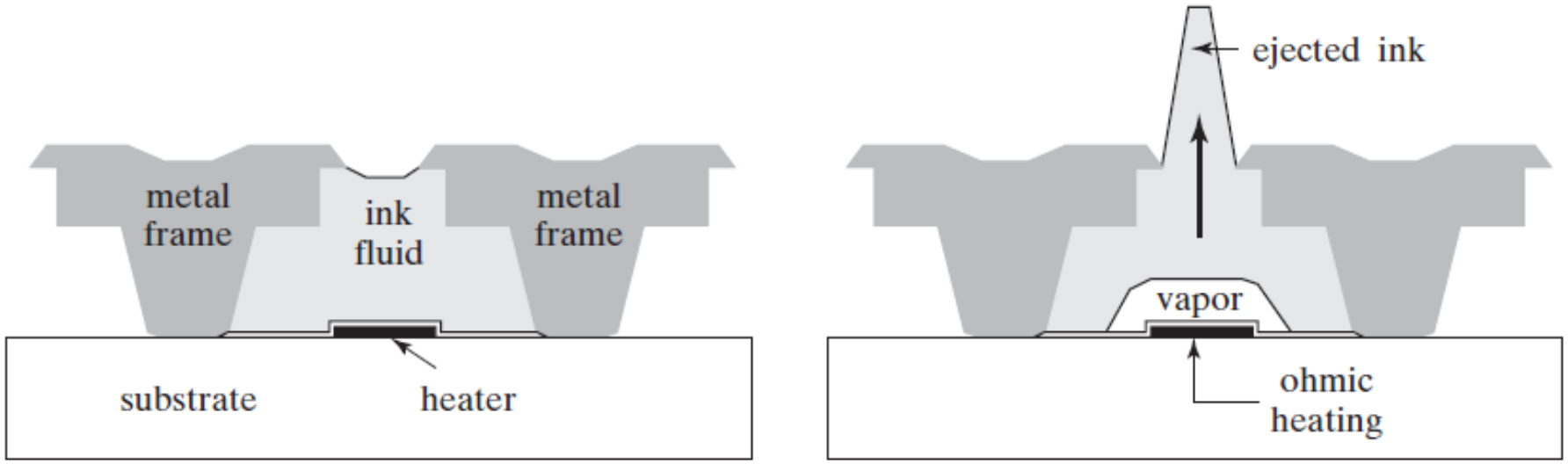


FIGURE 5.1

The principle of ink ejection.

- It consists of a micro machined fluid chamber with an opening. A micro heater is embedded on the substrate within the cavity. A pulse of electrical current raises the temperature of the heater and produces a vapor bubble that squeezes the liquid ink and ejects a droplet. Upon cooling, the vapor bubble collapses and the cavity is refilled with ink again for next firing.

Mechanisms of Heat Transfer

- There are four possible mechanisms for heat to move from one point to another:
  - **Thermal conduction** is the transfer of heat through a solid media in the presence of a temperature gradient.
  - **Natural** (passive) **thermal convection** is the transfer of heat from a surface into a stationary body of fluid. A temperature gradient in a fluid induces local flow movement through buoyancy. The movement of fluid mass facilitates heat transfer.
  - **Forced thermal convection** is the transfer of heat to a body of moving fluid. The bulk fluid movement provides enhanced heat transfer compared with that of natural convection.
  - **Radiation** represents the loss or gain of heat through electromagnetic radiation propagating in vacuum or air.

Governing Equations for Heat Transfer

Conduction: $$q''_{\text{cond}} = -k\frac{dT}{dx} \quad (5.1)$$

Natural and forced convection: $$q''_{\text{conv}} = h(T_s - T_\infty) \quad (5.2)$$

Radiation: $$E = \varepsilon\sigma T_R^4 \quad (5.3)$$

In these equations, q''_{cond} is conduction heat flux (W/m^2) along a given axis (designated x), κ the thermal conductivity, q''_{conv} the convection heat flux (W/m^2), h the convective heat transfer coefficient (W/m^2K), T_s and T_∞ the temperatures of the surface and fluid, respectively, E the emissive power, or the rate at which energy is released per unit area by radiation (W/m^2), T_R the absolute temperature (K) of a surface, σ the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}\ W/(m^2K^4)$), and ε the radiative emissivity (with values in the range $0 \le \varepsilon \le 1$).

The convective heat transfer coefficient is influenced by surface geometries, fluid velocity, viscosity, and thermal diffusivity. Typical values of the convective heat transfer coefficients are summarized in Table 5.1.

Convective Heat Transfer Coefficients

- The convective heat transfer coefficient is influenced by surface geometries, fluid velocity, viscosity, and thermal diffusivity. Typical values of the convective heat transfer coefficients are summarized in Table 5.1.

TABLE 5.1 Typical values of convection transfer coefficients.

		$h(\mathrm{W/m^2 \cdot k})$
Natural convection	Gases	2–25
	Liquids	50–1000
Forced convection	Gases	25–250
	Liquids	100–20,000
Convection with phase change (boiling or condensation)		2500–100,000

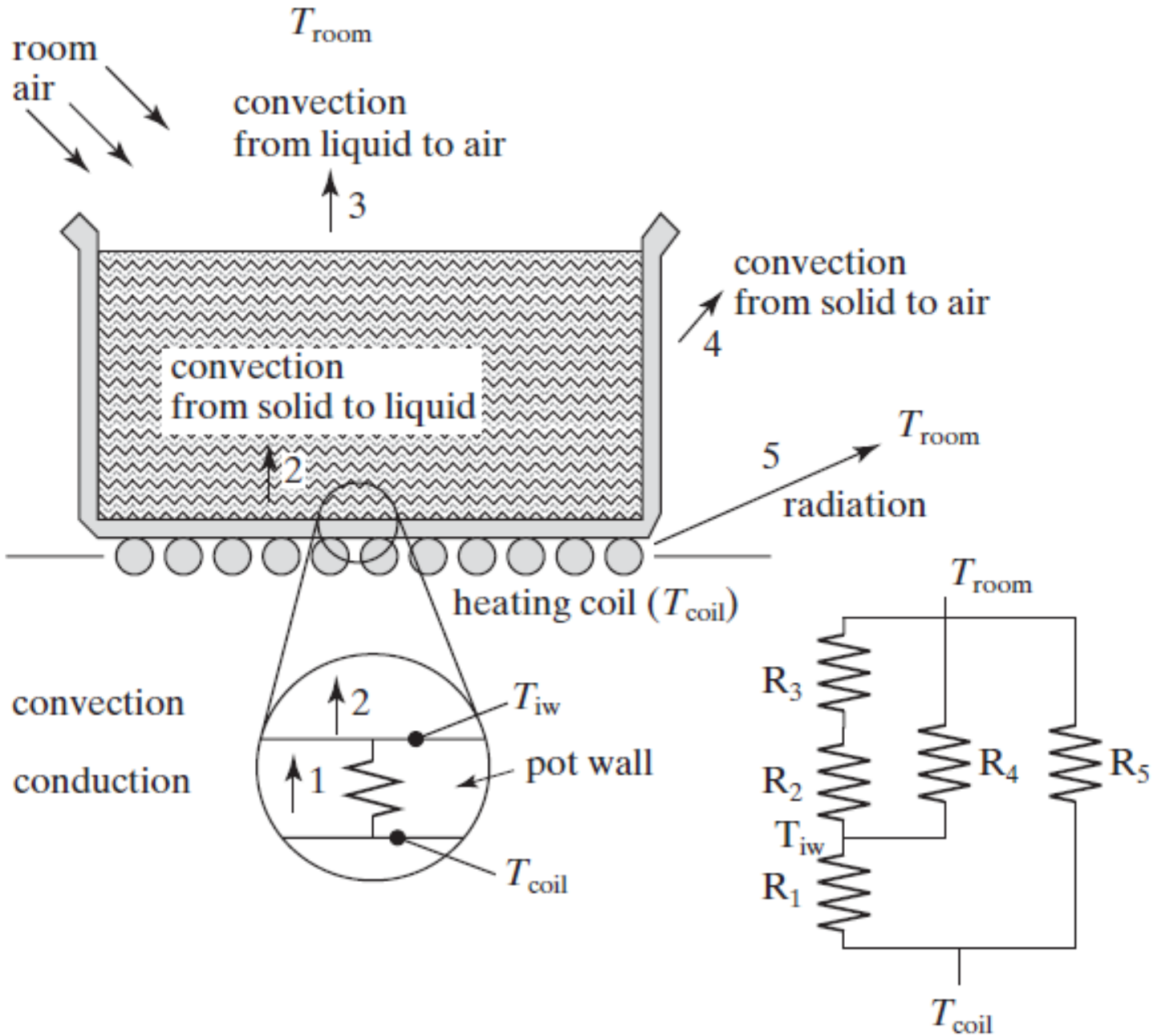


FIGURE 5.2

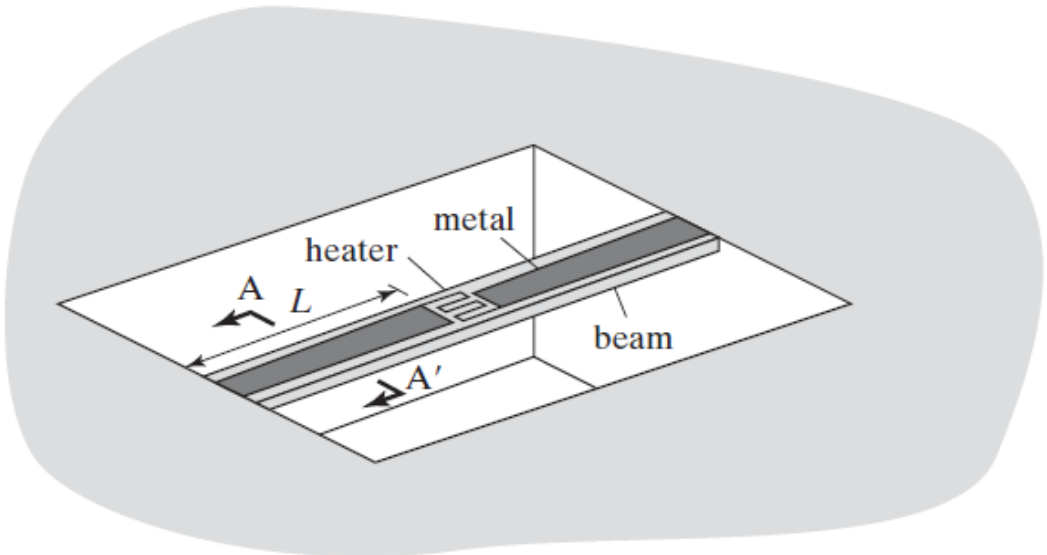
Heat transfer processes associated with pot heating.

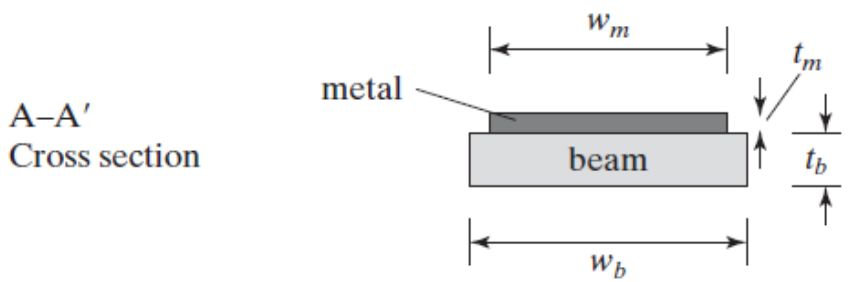
Pot Heating Example

- The heat produced by the heating coil first travels through the walls of the pot to reach the body of water inside. Heat transfer occurs within the thickness of the wall via *thermal conduction*.
- Once the heat reaches the interior wall of the pot, heat transfer to the liquid within begins. The liquid mass closest to the wall warms up and begins to rise, setting up a *natural convection*, which brings heat away from the pot wall to the interior of the body of water. If the liquid in the pot were stirred, the heat transfer from the inside wall of the pot to the liquid could become stronger as naturally convection is replaced by *forced convection*.
- The body of water is exposed to air at the top. If the air outside is still, heat will transfer from the water to the air through natural convection.
- On the other hand, if the air were moving (e.g., stirred by a fan), heat would travel from the hot liquid to the air by forced convection.
- Meanwhile, a person standing nearby feels heat wave coming from the heating coil. Heat is said to move through air by radiation.
- Assuming the heating coil is at a significantly high temperature, the radiation heat transfer can be quite strong. Certainly, the radiative dissipation reduces the energy efficiency of heating the water.

Example 5.1 Thermal Resistance of Suspended Bridge

A resistive ohmic heater is located in the middle of a suspended fixed-fixed cantilever. The beam is made of silicon nitride and the metal leads are made of aluminum. Find the numerical value of the thermal resistance experienced by the heater. Assume the width of the beam is 10 μm, $L = 100\,\mu$m, and the thickness of both aluminum (t_m) and silicon nitride (t_b) is 0.2 μm. If the input power to the heater is 0.1 mW, what is the steady temperature assuming the silicon bulk stays at 27°C?





Solution. The heater is connected to the substrate frame by four parallel connected thermal resistors, two of them contributed by the metal layer and two by the silicon beam. The substrate frame has much greater thermal mass than the bridge—its temperature is assumed to be a constant. The substrate frame is called a heat sink. Heat flow occurs between the heater and the substrate.

The thermal conductivity of aluminum and silicon nitride is 240 and 5 W/mK, respectively. The thermal resistance associated with each metal thermal resistor is

$$R_m = \rho_{\text{th},m}\frac{L}{W_m t_m} = \frac{1}{240} \times \frac{200 \times 10^{-6}}{0.2 \times 10 \times 10^{-12}} = 4.17 \times 10^5 \text{ K/W}$$

The thermal resistance associated with each silicon nitride beam is

$$R_{SiN} = \rho_{\text{th},SiN}\frac{L}{W_{SiN} t_{SiN}} = \frac{1}{5} \times \frac{200 \times 10^{-6}}{0.2 \times 10 \times 10^{-12}} = 2 \times 10^7 \text{ K/W}$$

These four resistors are connected in parallel. The total thermal resistance R is found by

$$\frac{1}{R} = \frac{2}{R_m} + \frac{2}{R_{SiN}}$$

The total resistance is

$$R = 2.042 \times 10^5 \text{ K/W}$$

If we ignore radiation heat loss and conduction/convection from the suspension to ambient air, the heat generated (1 mW) is entirely conducted through the bridge. Therefore, the total heat flux from the four parallel resistors is 0.1 mW. The temperature difference between the heater and the frame is

$$\Delta T = R \times 0.0001 W = 20.4 \text{ K}$$

Significance of Rate of heating & cooling

In many devices, the speed at which the temperature of a microstructure can rise or fall is critical. The heating and cooling speed of an ink jet printer determines the maximum printing speed, for example. The thermal resistance influences the dynamic response speed of a thermal sensor or actuator.

The relationship between stored thermal energy (Q) and temperature change is

$$Q = sh \cdot m \cdot \Delta T = C_{\text{th}} \cdot \Delta T, \tag{5.7}$$

where sh (J/kgK) is the **specific heat**, which is the amount of heat per unit mass required to raise the temperature of an object by one degree Celsius or Kelvin. The term C_{th}(J/K) is called the **heat capacity**, which is the equivalent of electrical capacitance in a thermal-electrical analogy. The general expression of the time constant associated with heating or cooling of a microstructure is

$$\tau = R_{\text{th}} C_{\text{th}} = R_{\text{th}} \cdot sh \cdot m \tag{5.8}$$

The small mass of microstructures favors the reduction of time constant.

Sensors & Actuators Based on Thermal Expansion

Thermal expansion is an omnipresent behavior of materials. The dimensions and volume of structures made of semiconductors, metals, and dielectric materials would increase upon temperature rise. The **volumetric thermal expansion coefficient** (TCE), commonly denoted as α, is the ratio between relative change of volume to the degree of temperature variation,

$$\alpha = \frac{\frac{\Delta V}{V}}{\Delta T} \tag{5.9}$$

The **linear expansion coefficient** is the change of only one dimension of an object due to temperature variation,

$$\beta = \frac{\frac{\Delta L}{L}}{\Delta T} \tag{5.10}$$

TABLE 5.2 Selected thermal properties of common materials.

Material	Thermal conductivity (W/cm K)	Linear temp. coefficient of expansion
Aluminum	2.37	2.5
Aluminum oxide	0.36	8.7
Aluminum oxide	0.46	–
Carbon	0.016	–
Carbon	23	–
Cr	0.94	6
Cu	4.01	16.5
GaAs	0.56	5.4
Ge	0.6	6.1
Au	3.18	14.2
Si	1.49	2.6
SiO_2 (thermal)	0.0138	0.35
SiN (silicon)	0.16	1.6
Polyimide (Dupont PI 2611)	–	3
Poly silicon	0.34	2.33
Ni	0.91	13
Ti	0.219	8.6

The volumetric and linear expansion coefficients are related by

$$\alpha = 3\beta.$$

The linear thermal expansion coefficients of representative organic and inorganic materials are summarized in Table 5.2. Apparently, the value of the thermal expansion coefficient for most solid materials is small. The extent of expansion is rather limited for practical values of temperature rise. For instance, upon a temperature rise of 100°C, a 1-mm-long silicon cantilever will only elongate by a distance of $2.6 \times 10^{-6} \times 100 \times 10^{-3} = 2.6 \times 10^{-7}$ m $= 0.26\ \mu$m.

It should be noted that for thin film materials such as silicon nitride and polycrystalline silicon films, thermal properties such as thermal expansion coefficient depend on the exact composition of the material, determined by specific process settings, equipment settings, and thermal treatment history. Data on thermal properties collected from literature vary quite widely. Furthermore, many data points in Table 5.2 are collected from bulk materials and should only serve as a reference when dealing with microscopic samples. Representative thermal properties of commonly used metals are summarized in Table 5.3.

Actuators based on thermal expansion of liquid or air have been achieved in the past [5, 7]. The thermal expansion coefficients of many liquids are greater than those of solids. The value of α for water above 40°C is approximately 400 ppm/K. Some special engineered fluids have even greater α. For example, the volumetric thermal expansion coefficients of 3M performance fluids are in the range of 0.16%/K [5].

TABLE 5.3 Thermal and electrical properties of metal thin films.

Material	Resistivity ($\mu\Omega$cm)	Thermal conductivity (W/cmK)	TCR (ppm/°C)	Coefficient of thermal expansion (ppm/K)
Aluminum (Al)	2.83	2.37	3600	25
Chromium (Cr)	12.9	0.94	3000	6.00
Copper (Cu)	1.72	4.01	3900	16.5
Gold (Au)	2.40	3.18	8300	14.2
Nickel (Ni)	6.84	0.91	6900	13
Platinum (Pt)	10.9		3927	8.8

Thermal Bimorph Principle

The thermal bimetallic effect is a very commonly used method for sensing and actuation. This mechanism allows temperature variation in microstructures to be exhibited as transverse displacement of mechanical beams.

The thermal bimorph consists of two materials joined along their longitudinal axis serving as a single mechanical element [8]. (Oftentimes, a thermal bimetallic actuator may consist of more than two layers of materials. This book focuses on the analysis of two-layered architectures only.) Figure 5.3 shows a composite beam with two layers, made of material 1 and 2, having same length (L) but different coefficients of thermal expansion (CTE) ($\alpha_1 > \alpha_2$). The subscript refers to the material layer. Likewise, the Young's modulus, width, and thickness of the two layers are denoted E_i, w_i, and t_i ($i = 1$ or 2). With a uniform temperature rise of ΔT, the length of two sections changes unequally. Because the two-layered materials are tightly joined at the interface, the beam must curve toward the layer made of the material with a lower CTE value. A transverse beam bending is therefore produced.

Next we analyze the formula for calculating the displacement of a bimetallic beam. Under a uniform temperature change of ΔT, the beam curves and assumes the shape of a section of an

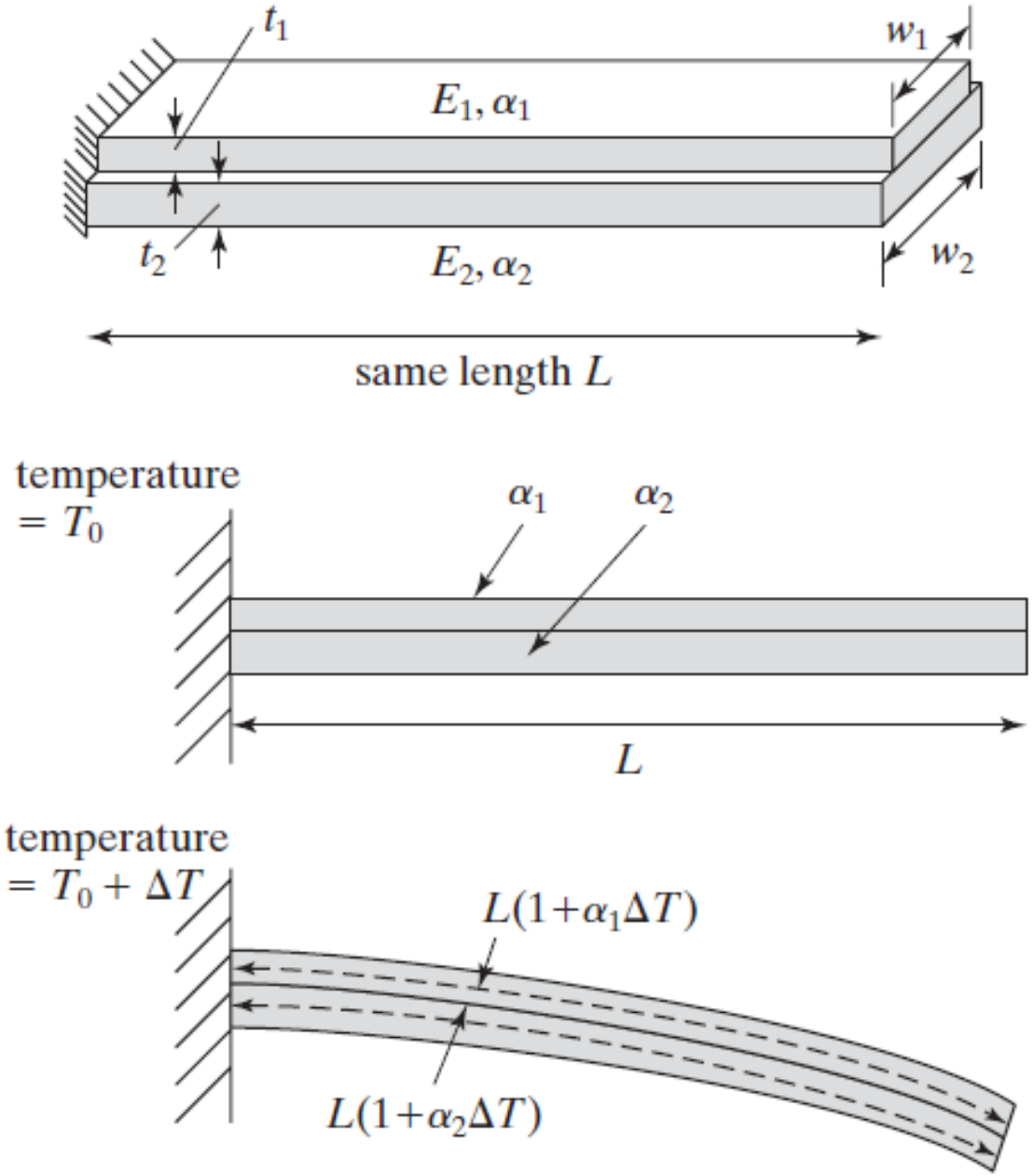


FIGURE 5.3

Thermal bimetallic bending ($\alpha_1 > \alpha_2$).

arc with the length of the arc being L. The radius of curvature of the arc, r, can be calculated using this formula:

$$\frac{1}{r} = \frac{6w_1w_2E_1E_2t_1t_2(t_1 + t_2)(\alpha_1 - \alpha_2)\Delta T}{(w_1E_1t_1^2)^2 + (w_2E_2t_2^2)^2 + 2w_1w_2E_1E_2t_1t_2(2t_1^2 + 3t_1t_2 + 2t_2^2)} \tag{5.14}$$

The arc is a section of a circle with the radius of curvature being denoted r, spanning an arc angle θ.

The value of θ is determined by

$$\theta = l/r. \tag{5.15}$$

Once the radius of curvature is found, the vertical displacement of the free end of the beam can be determined by trigonometry according to Figure 5.4.

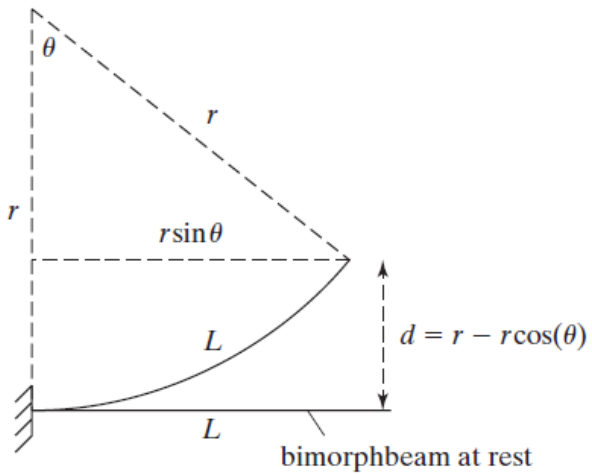


FIGURE 5.4
Geometry of a bent beam.

The vertical displacement at the free-end of the cantilever is therefore

$$d = r - r\cos\theta \tag{5.16}$$

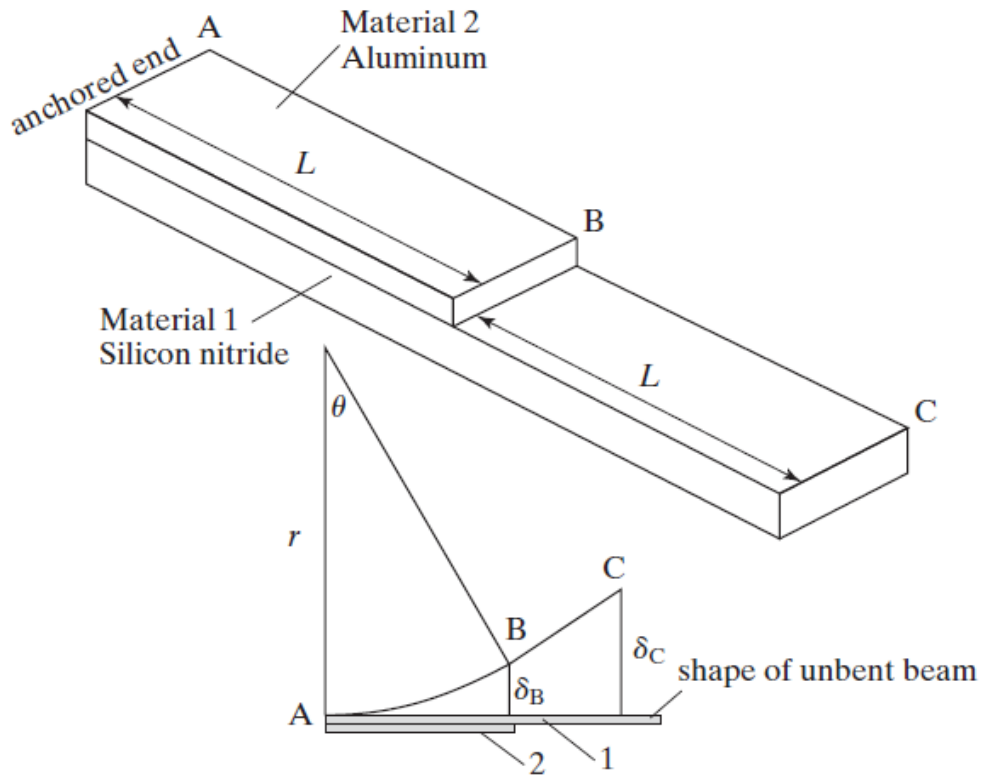
If the overall bending angle is small, the magnitude of the vertical displacement can be estimated by replacing $\cos\theta$ with first two terms in its Taylor series expansion:

$$d = r - r\left(1 - \frac{1}{2}\theta^2 + O(\theta^4)\right) \approx \frac{1}{2}r\theta^2 \tag{5.17}$$

Example 5.2 Displacement of a Bimetallic Actuator

A bimetallic cantilever beam is made of two layers of different lengths. The layer on top is made of aluminum (Material 2), whereas the layer on the bottom is made of silicon nitride (Material 1). The width of both layers is 20 μm. The length of the segment between point A and B is 100 μm, so is the length of the segment from point B to C. The Young's modulus of aluminum and silicon nitride are $E_2 = 70$ GPa and $E_1 = 250$ GPa, respectively. The thickness of aluminum and silicon nitride sections is $t_2 = 0.5\,\mu$m and $t_1 = 1\,\mu$m, respectively. The thermal expansion coefficients of aluminum and silicon nitride are $\alpha_2 = 25$ ppm/°C and $\alpha_1 = 3$ ppm/°C, respectively. At room temperature, the cantilever is straight.

Find the radius of curvature (r) of the cantilever beam when the beam is uniformly heated to 20 °C above the room temperature. Determine the amount of vertical displacement at the free end of the beam under this condition.



Solution. The composite beam consists of two segments. The segment spanning point A and B undergoes curvature bending due to the thermal bimetallic effect. The segment spanning point B and C consists of only a single layer of material. It will not undergo curvature bending but will follow the angular bending that takes places at point B.

For segment A-B, we can write the expression for the radius of curvature as

$$\frac{1}{r} = \frac{6w_1w_2E_1E_2t_1t_2(t_1 + t_2)(\alpha_1 - \alpha_2)\Delta T}{(w_1E_1t_1^2)^2 + (w_2E_2t_2^2)^2 + 2w_1w_2E_1E_2t_1t_2(2t_1^2 + 3t_1t_2 + 2t_2^2)}$$

$$= \frac{6(400 \times 10^{-12})(70 \times 250 \times 10^{18})0.5 \times 10^{-12}(1.5 \times 10^{-6})(22 \times 10^{-6})20}{2.5 \times 10^{-11} + 1.225 \times 10^{-13} + 7(4 \times 10^{-12})}$$

$$= \frac{1.386 \times 10^{-8}}{5.3 \times 10^{-11}} = 260.9\ \text{m}^{-1}.$$

The radius of curvature in the segment A-B is

$$r = 0.00383\ \text{m}.$$

The angle spanned by the curved section is

$$\theta = \frac{L}{r} = \frac{0.0001}{0.00383} = 0.026\ \text{rad} = 1.49°.$$

The vertical displacement at point B is

$$\delta_B = r - r\cos(\theta) = 1.3 \times 10^{-6}\ \text{m}.$$

The vertical displacement at point C is

$$\delta_C = \delta_B + L\sin(\theta) = 3.9 \times 10^{-6}\ \text{m}.$$

The thermal bimetallic displacement can be used for both sensing and actuation purposes. It is in fact the mechanism for many household electromechanical thermostats. A conventional thermostat consists of a spiral bimorph metal coil. The end of the coiled beam is attached to an electrical relay, in the form of a sealed glass vial containing a drop of mercury. When the environmental temperature changes, the end of the coil would tilt and trigger movement of the mercury-drop relay to regulate current flow in heating/cooling circuitry.

Several examples of micromachined bimetallic temperature sensors are discussed in Section 5. In the remainder of this section, we will focus on thermal bimetallic actuators.

As a component of an actuator, a thermal bimaterial beam can produce angular and linear displacements. It is interesting to draw comparison between the two actuation methods we have studied so far—electrostatic actuation and thermal actuation. Both electrostatic and thermal bimetallic actuation methods are commonly used in MEMS. The relative merits and disadvantages of both methods are summarized in the Table 5.4.

Two examples of thermal bimetallic actuators are reviewed below, both for transporting micro objects. The actuator in Case 5.1 does not incorporate integrated circuits for control purposes, whereas the one in Case 5.2 is integrated with on-chip electronics.

Comparison

TABLE 5.4 Characteristics of electrostatic and thermal bimetallic actuation.

	Electrostatic Actuation	Thermal Bimetallic Actuation
Advantage	1. Low power operation at low frequencies. 2. High response speed.	1. Relatively large range of movement can be achieved. 2. Small actuator footprint for comparable displacement.
Disadvantage	1. Relatively small range of motion. 2. Requires large area and footprint in order to generate large force and displacement.	1. Moderate to high power operation as current is used to generate ohmic heating. 2. Lower response speed as the time constant is governed by thermal heating and dissipation.

Case Studies

Case 5.1 Bimetallic Artificial Cilia Actuator

In microelectronics manufacturing, the handling and assembly of small objects such as dies cut from a wafer is generally labor intensive and inefficient. A technology is needed for small chips to be transported and oriented efficiently in the production line. An array of thermal actuators, mimicking biological cilia, have been developed to carry and transport a small object laterally in a plane [9]. According to Figure 5.5, an object is supported by the array of out-of-plane cilia. These actuators are divided into two groups that are activated out of phase with respect to each other. Power is applied to these two groups of actuators with at a certain clock frequency.

At the start of a cycle, both groups of actuators are elevated to hoist a small object (Figure 5.5a). One group is actuated and lowered first (Figure 5.5b). Another group is lowered later, causing the object it carries to move forward by a small amount (Figure 5.5c).

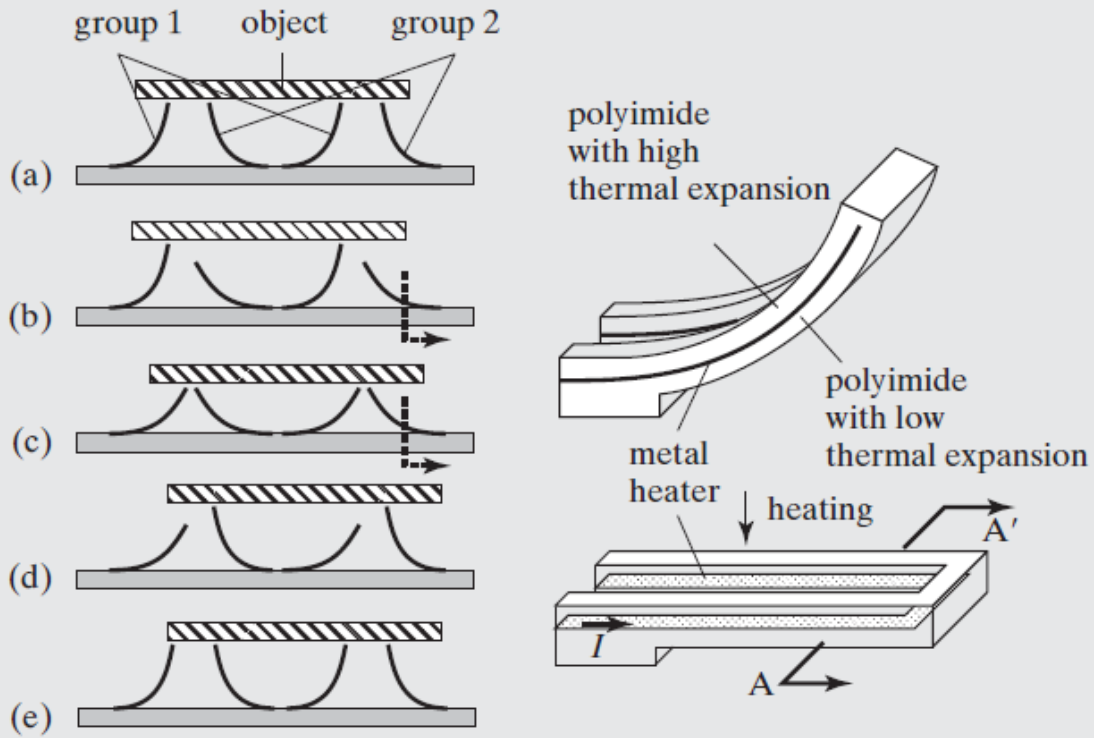


FIGURE 5.5

Artificial cilia array for object transport.

The group that was lowered first is returned to the elevated position, moving the object by a small distance again. The second group of actuators is then elevated, returning the system to its starting configuration. Actuators belonging to the first group are released to complete a cycle (Figure 5.5d). Through each cycle, the object is moved by a small incremental distance. Long distance movement of the object result through repeated cycles.

Each cilium is a curved bimorph cantilever, 500 μm long, 100 [illegible] thick (Figure 5.5). The top view of the cantilever reveals a folded wire [illegible] of wire associated with each wire loop is 30–50 Ω. The cross section c[illegible] layers—a polyimide layer with high thermal expansion coefficient, a[illegible] other bottom polyimide layer with a lower thermal expansion coeff[illegible] layers as well as metal layers exhibit tensile intrinsic stress to raise the [illegible] rest. When electrical current passes through the resistor, the gold and [illegible] heated. Because the top polyimide layer has greater thermal expansio[illegible] tilever bends downward. Large displacement can be achieved. For e[illegible] placement of 250 μm and companion horizontal displacement of 80 μ[illegible] mA drive current is used, corresponding to a power dissipation of 33 m[illegible]

The fabrication process can be carried out on bare silicon or glass wafer. A four-mask fabrication process (Figure 5.6) begins with deposition of a 1.6-μm-thick aluminum thin film, serving as a sacrificial layer (step a). A layer of polyimide is spin coated and patterned, to form a 2.2-μm-thick film (step b). Metal thin film patterns (200-nm-thick gold and 100-nm-thick nickel) are formed by evaporation and patterned by wet etching (step c). Adhesion between the gold and polyimide is enhanced significantly by the use of the nickel adhesion layer. The authors coated another layer of polyimide again, to a thickness of 3.6 μm (step d).

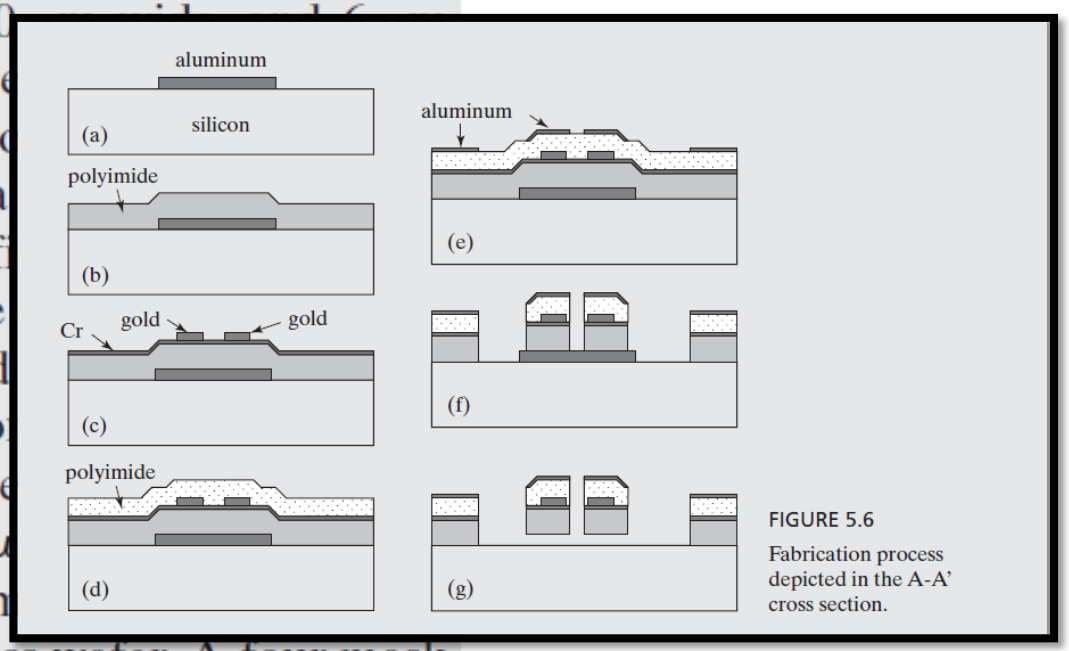


FIGURE 5.6
Fabrication process depicted in the A-A' cross section.

This polyimide layer needs to be patterned. One option is to use photo definable polyimide. The authors did not use this approach. One possible reason is that photo patternable polyimide with suitable TCE value cannot be found.

Instead, a polyimide layer is deposited and later patterned by etching. It was determined that plasma etching is the best course for minimizing undercut. In order to pattern this layer of polyimide, it needs to be masked by a protective layer. Both metal thin films and photoresist may serve as the protective layer. Photoresist, however, does not provide sufficient etch selectivity. As a consequence, the top polyimide is coated with a layer of thin film metal. The thin film metal is patterned photolithographically and etched (step e). It then serves as a mask for a subsequent etching of the polyimide layer using oxygen plasma, to define the polyimide beams (step f). The sacrificial layer is removed in selective regions to release the polyimide beams (step g).

Demonstration of the cilia array carrying a 2.4 mg silicon wafer traveling at 27–500 μm/s with 4 mW input for each actuator has been successfully made

Case 5.2 Bimetallic Actuators for Object Transport

The cilia actuators remain in down positions for a significant fraction of the cycle. The cilia transport chip discussed in Case 5.1 requires constant power input to keep a cilia in its down position. This translates into rather significant power consumption.

Researchers later developed a improved version of thermal actuator for transporting objects in a two dimension plane [10] (Figure 5.7). Each flap-shaped cilia actuator consists of a metal resistive heater as well as thin film electrode plate. The two materials of different thermal expansion coefficients are both polymer materials. One polymer is PIQ-L200, with a TCE value of 2.0 ppm/°C. Another one is PIQ-3200, 54 ppm/°C. The metal film is sandwiched between two polyimide layers, serving as heater and one electrode of a parallel capacitor. A counter electrode is located on the substrate surface.

Each flap is bent out of plane under zero applied power because of intrinsic stress in the materials. Upon applied ohmic heating, a flap bends towards the substrate surface. Instead of using a constant current to keep the cilia down, electrostatic actuation can be used to hold the flap position. When the flap is parallel to the substrate plane, the magnitude of the electrostatic force is the greatest due to close proximity of electrodes. The electrostatic force is energy efficient for static position holding, consuming virtually no power.

Later, the group changed the geometries of the thermal manipulator and integrated them on a substrate with CMOS controller electronics [11]. The design of each actuator is considerably simpler than the previous generation—the electrodes for electrostatic holding is removed, perhaps because it is expensive to integrate parallel capacitors with large footprint onto CMOS chips. The heater is made of Ti-W heater resistor with 1 kΩ resistance each. A DC power input of 35–38 mW produces a vertical displacement of 95 μm accompanied by a

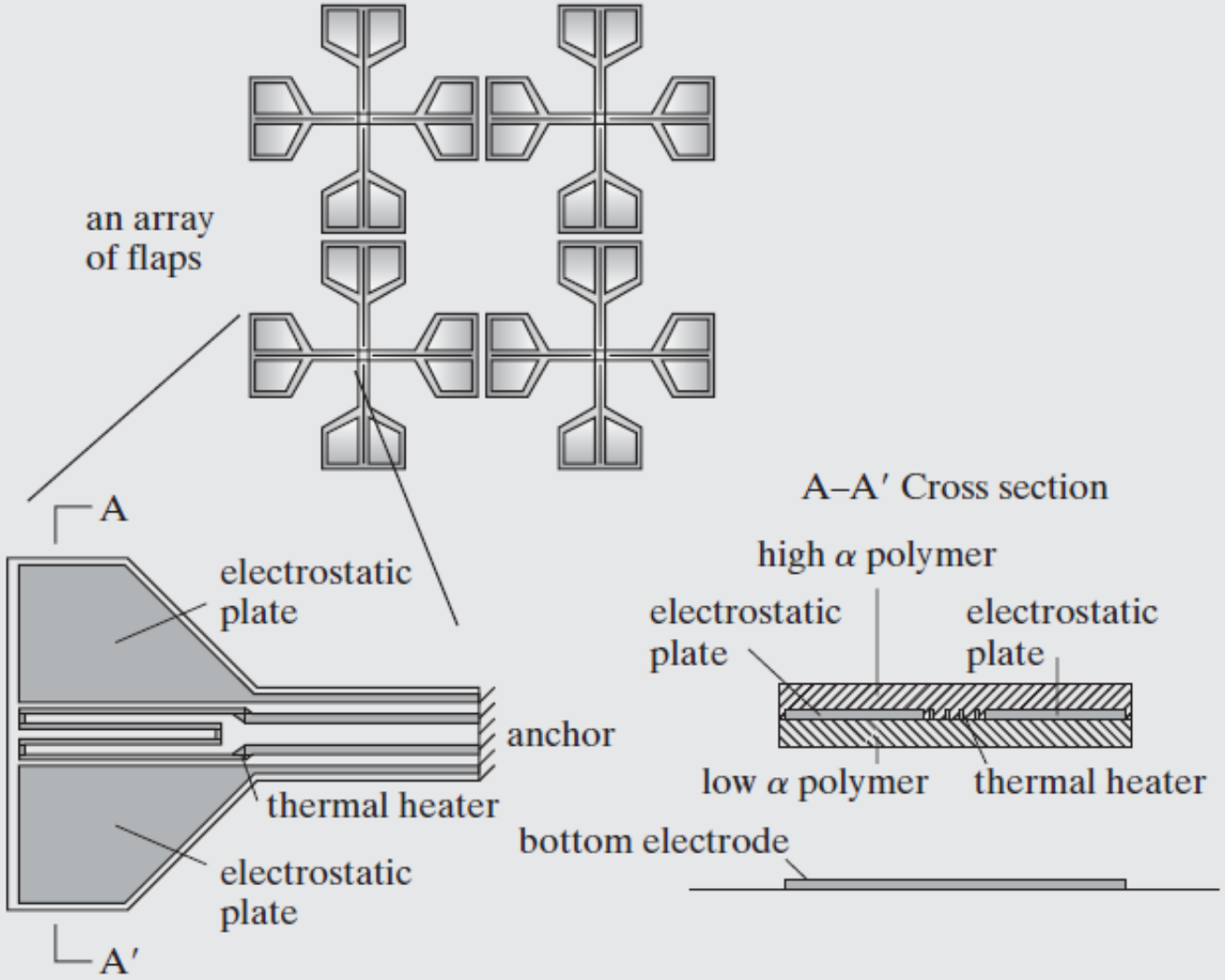


FIGURE 5.7

Polyimide thermal actuator.

17 μm lateral displacement. An array was programmed to perform simple linear and diagonal translations and squeeze-, centering-, and rotating-field manipulation of silicon pieces of various shapes. In year 2010, the group developed micro robots based on the thermal actuator concept [12].

Thermal Actuators with a Single Material

Thermal bimorph bending is convenient for creating out-of-plane linear or angular displacement. It can produce in-plane displacement provided that the layered thermal bimorph materials are stacked on vertical surfaces. However, the fabrication process for such stacked structures is rather difficult.

Thermal actuators based on a single material for generating in-plane motion has been demonstrated, for example by using bent-beam electrothermal actuators [13]. The schematic diagram of a representative bent-beam actuator is shown in Figure 5.8. A bent beam is made of silicon doped to a certain concentration; it serves as the ohmic heater as well. Current passing through the bent beam causes two branches to expand, resulting in tip motion in the

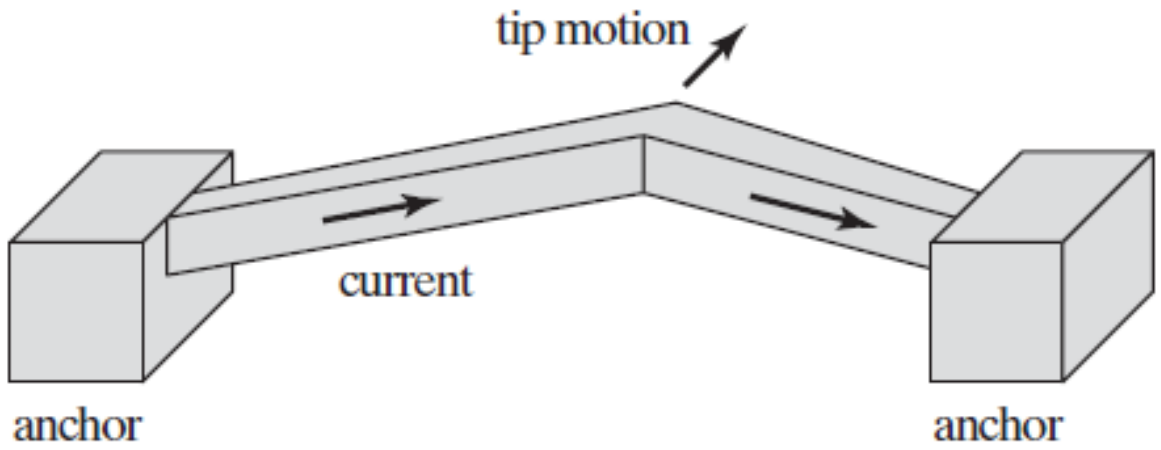


FIGURE 5.8

A bent-beam electrothermal actuator.

transverse direction. The beam is capable of producing peak output force on the order of 1–10 nN with a driving voltage of less than 12 V. Static displacement on the order of 10 μm at 79 mW input power has been demonstrated with beams that are 410 μm long, 6 μm wide, and 3 μm thick.

Alternative configurations of thermal actuators based on a single material are discussed in Case 5.3.

The output force can be further increased by connecting many actuators in parallel [14].

Case 5.3 Lateral Thermal Actuators

Lateral driven thermal actuators based on asymmetrical thermal expansion of a microstructure with two arms made of a same conductive material have been realized. These two arms have different heating power and thermal expansion, resulting in difference of longitudinal expansion when a current passes through. Two strategies have been demonstrated:

1. An actuator may consist of two beams with the same cross-sectional area but different length [15]. The longer arm is associated with greater electric resistance and thermal resistance. By passing an identical current through the loop, the longer arm will produce higher temperature and greater expansion, causing the tip to bend towards the

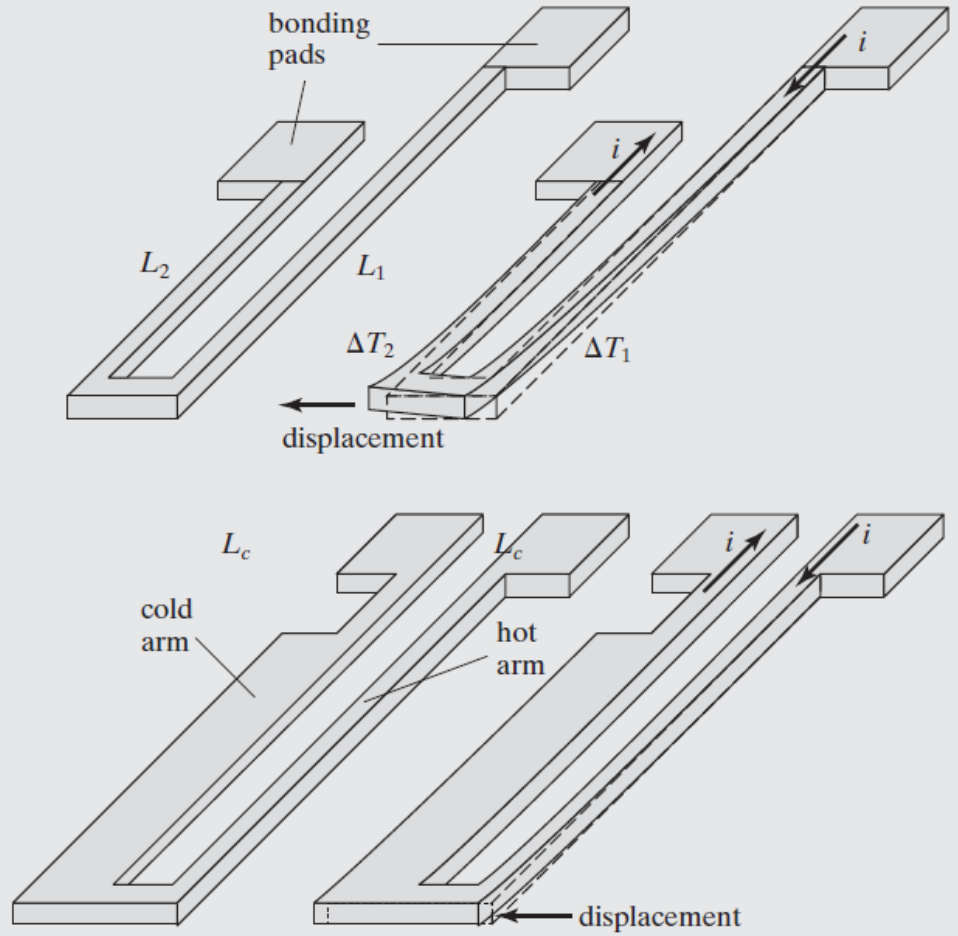


FIGURE 5.9
Lateral thermal actuators.

direction of the shorter arm. An actuator was tested, with the long beam being 500 μm long and the short one 300 μm long. The width and thickness of the beams are 2.8 and 2 μm, respectively. Lateral displacement as large as 9 μm has been demonstrated under a bias voltage of 14 V. The resistivity, Young's modulus, Poisson's ratio, and density of the arms are 5×10^{-6} Ωcm, 150 GPa, 0.066, and 232-kg/m^3, respectively.

2. An actuator may contain two beams with same length but different cross-sectional area [16–19]. The arm with a smaller cross section is called the hot arm. The one with a larger section, cold arm. Under a same current, the hot arm reaches high temperature and therefore greater linear expansion. An actuator with the hot arm being 2.5 μm wide, 240 μm long, cold arm being 16 μm wide, and 200 μm long was able to generate 16 μm displacement at 3 V and 3.5 mA for a 2-μm-thick polysilicon layer. Modeling has been performed [19]. The thermal actuator can be connected together to generate large force [17] for various applications including optical aligners.

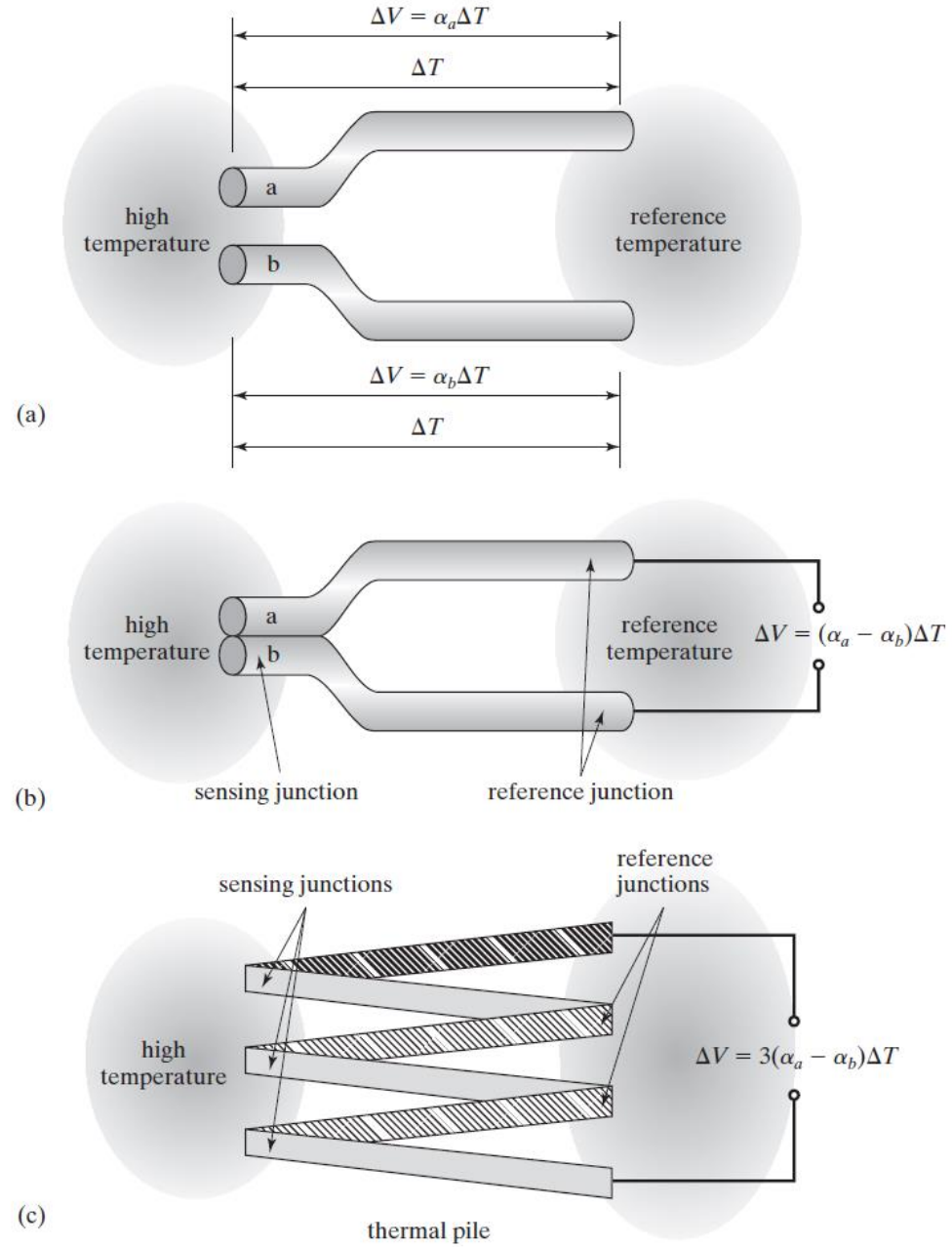
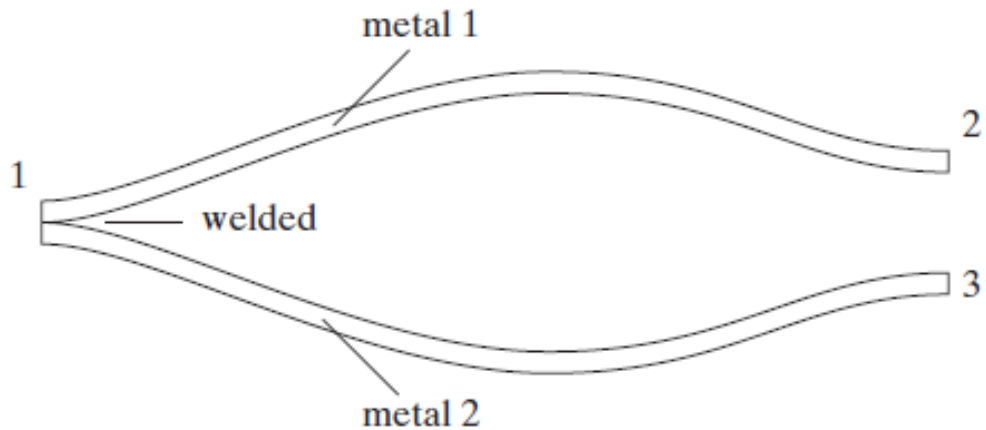


FIGURE 5.10

A thermal couple element.

Problem 6: Design

Two pieces of metal wires are connected in a thermal couple configuration as follows. The temperature at point 1 is higher than the temperatures at points 2 and 3. There are three possible metals. (1) Chromel, with Seeback coefficient $= 30\,\mu$V/K), (2) Alumel, with Seeback coefficient $= -11\,\mu$V/K, (3) Iron, with Seeback coefficient $= 10\,\mu$V/K. Which of the following statement would be correct? Which one gives the best temperature sensitivity? Show your analysis steps.



1. Metal 1 = Chromel, Metal 2 = Chromel, produces maximum possible thermal couple sensitivity of 60 μV/K;
2. Metal 1 = Alumel, Metal 2 = Chromel, produces maximum possible thermal couple sensitivity of 30 μV/K
3. Metal 1 = Iron, Metal 2 = Alumel, produces maximum possible thermal couple sensitivity of 21 μV/K
4. Metal 1 = Chromel, Metal 2 = Alumel, produces maximum possible thermal couple sensitivity of 41 μV/K.

Answer: _____

Problem 7: Design

Three polysilicon thermal resistors with the TCR values of (1) Resistor 1, $\alpha = 1000$ PPM/°C,(2) resistor 2, $\alpha = 2000$ PPM/°C, and (3) resistor 3, $\alpha = -1000$ PPM/°C. An I–V curve measurement is conducted on these three resistors. Which of the following I–V and R–P curves (A through F) are likely to be true? Explain your analysis.

1. A
2. B
3. C
4. D
5. E
6. F

Answer: _____